Numerical Investigations of Vortex-Induced Vibration of Two-Dimensional Circular Cylinder Experiencing Oscillatory Flow

Di Deng, Zhe Wang, Decheng Wan*
State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Collaborative Innovation Center for Advanced Ship and Deep-Sea Exploration, Shanghai, China
*Corresponding author

ABSTRACT

Sinusoidal motion of a cylinder in viscous flow has been extensively studied in the past decades. Distinction of flow patterns exists between cylinders in cross-flow freedom restricted and freely vibrating conditions when experiencing oscillatory flow. In this paper, a series of numerical simulations are carried out by the in-house CFD code naoe-FOAM-SJTU, which is developed basing on the open source code OpenFOAM with overset grid capability. The diameter of the cylinder is 0.02m and the KC numbers varies from 3 to 12 corresponding to the attached vortices regime and the transverse street regime. Results of vortex evolution, flow regimes and hydrodynamic force coefficients are compared.

KEY WORDS: naoe-FOAM-SJTU solver; Overset grid method; KC numbers; Vortex-induced Vibration

INTRODUCTION

In actual production, offshore floating structures subject to waves, currents or winds will cause the platform to move periodically in the water. Then relatively oscillatory flow is generated between the riser and the water. In recent decades, researches of the sinusoidal motion of a cylinder in viscous fluid have been extensively studied by Bearman (1984, 1985), Sarpkaya (1986, 1995) and Williamson (1985).

Williamson (1985) conducted a series of experiments to investigate development of vortices around a single cylinder in relative oscillatory flow. And several vortex regimes were identified within particular ranges of Keulegan-Carpenter (KC) Numbers: the attached vortices regime (0<KC<7), where no major vortices shed during a cycle; the single pair regime (7<KC<15); the double pairs regime (15<KC<24); the three pairs regime (24<KC<32) and the four pairs regime (32<KC<40). For further KC regimes, the number of vortices pairs shed in each oscillating period would be increased by one each time the KC regime changed to a higher one.

Kozakiewicz et al., (1996) conducted experiments of a cylinder exposed to oscillatory flow for two Keulegan–Carpenter numbers, KC=10 and 20. Then numerical simulations of a cylinder freely vibrating in the cross-flow direction were carried out at the same KC numbers. Comparisons showed that the number of vortices generated over one oscillating cycle increased when the cylinder was freely vibrating in the cross-flow direction. The vortex shedding direction changed to the opposite side of the cylinder in the transverse street regime when KC=10.

Zhao et al., (2011) carried out numerical investigations of VIV of a circular cylinder in oscillatory flow following experiments of Kozakiewicz et al., (1996). He found that the reduced velocities had significant effects to the XY- trajectory mode of the cylinder. The VIV frequency decreased with the
increase of the reduced velocity. When the reduced velocity was extremely large, the vibration amplitude in the cross-flow direction was negligible smaller than that of the inline direction.

Nguyen and Temarel (2014) conducted numerical simulations of flow past a circular cylinder in uniform cross-flow using a 2D RANS method for three cases: a forced oscillating cylinder, a forced oscillated cylinder and a freely vibrating cylinder. Results of drag and lift coefficients were in good agreement with former experiments. Essential features of fluid and structure interaction were captured through the simulations.

Other researchers also had conducted studies on oscillatory flow around a circular cylinder through numerical and experimental methods, such as An et al., (2011), Graham (1980), Nehari et al., (2004) and Tatsuno and Bearman (1990).

In this paper, numerical simulations are carried out by the in-house CFD code naoe-FOAM-SJTU. The solver is developed basing on the open source platform OpenFOAM with overset grid capability. The Reynolds Averaged Navier-Stokes (RANS) equations are adopted to obtain the flow field. The 6DoF equations are used to compute the motion of the cylinder. Firstly, the grid convergence study is conducted to verify that the solution is insensitive to the grid resolution at $KC=3$ for the forced oscillating cylinder. Then, simulations and comparisons between forced oscillating cylinder and freely vibrating cylinder experiencing relative oscillatory flow at $KC=6$ and $12$ are conducted.

This paper is organized as follows: The first section gives a brief introduction to the numerical methodology used in this paper. The second section presents results of grid convergence study, numerical simulations and comparisons at $KC=6$ and $12$ respectively. The final section concludes the paper.

METHODOLOGY

The in-house CFD code naoe-FOAM-SJTU (Shen and Wan, 2012) is used in this paper, which is developed basing on OpenFOAM combined with the overset grid program Suggar++. The Reynolds Averaged Navier-Stokes (RANS) equations are adopted to obtain the flow field. The 6DoF equations are used to compute the motion of the cylinder. Firstly, the grid convergence study is conducted to verify that the solution is insensitive to the grid resolution at $KC=3$ for the forced oscillating cylinder. Then, simulations and comparisons between forced oscillating cylinder and freely vibrating cylinder experiencing relative oscillatory flow at $KC=6$ and $12$ are conducted.

This paper is organized as follows: The first section gives a brief introduction to the numerical methodology used in this paper. The second section presents results of grid convergence study, numerical simulations and comparisons at $KC=6$ and $12$ respectively. The final section concludes the paper.

Hydrodynamic Governing Equations

In this paper, the flow field is supposed to be incompressible with constant dynamic viscosity $\mu$ and constant density $\rho$. The Reynolds-averaged Navier-Stokes (RANS) equations combined with SST $k-\omega$ turbulent model are used to obtain hydrodynamic response of the cylinder. The hydrodynamic governing equations are shown as follows:

$$\frac{\partial \vec{\sigma}}{\partial \vec{x}} = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \frac{\partial}{\partial x_j} \left( \rho \vec{u} \vec{u}_j \right) = -\frac{\partial \vec{p}}{\partial x_j} + \frac{\partial}{\partial x_j} \left( 2\mu \bar{S}_{ij} - \rho \mu' \right) \quad (2)$$

where $\bar{S}_{ij} = \frac{1}{2} \left( \frac{\partial \vec{u}_i}{\partial x_j} - \frac{\partial \vec{u}_j}{\partial x_i} \right)$ is the mean rate of strain tensor, $-\rho \mu' \mu''$ is referred as Reynolds stress $\tau'_y$ defined as $\tau'_y = -\rho u'_i u'_j = \tau''_{ij} - \frac{2}{3} \rho k \delta_{ij}$ where $\mu'$ is the turbulent viscosity and $k = (1/2)\bar{u}'_i \bar{u}'_j$ is the turbulent energy, computed from the fluctuating velocity field.

Cylinder Motion

Fig. 1 shows the sketch of computational domain of the freely vibrating cylinder in cross-flow section. The diameter of the circular cylinder is $D=0.02m$. The rectangular computational domain is $40D$ in the flow direction and $30D$ in the cross-flow direction. The cylinder is located in the center of the domain and restrained with 4 springs of equal rigidity setting along the x-axis and y-axis. The cylinder is forced to oscillate in the flow direction ($x$ direction) and allowed to vibrate in the cross-flow direction ($y$ direction). The 4 springs are only active for freely vibrating cases. The displacement of the cylinder can be written as:

$$A(t) = A_e \cos(\omega \tau + \varphi) \quad (3)$$

where $A_e$ is the amplitude of the forced motion, $\omega = \frac{2\pi}{T}$ is the circular frequency and $T$ is the oscillating period of the cylinder, $t$ is the time and $\Phi$ is the phase angle.
Parameters of the system influence the cross-flow vibration of the cylinder are as follows: (1) the mass ratio: \( m' = m / m_j \), where \( m \) is the mass of the cylinder and \( m_j = \rho g \pi D^2 / 4 \) is the mass of the displaced fluid; (2) the Keulegan-Carpenter (KC) number: \( KC = 2 \pi \cdot A_p / D \); (3) the Reynolds number: 
\[
Re = U_m D / \nu ,
\]
where \( U_m \) is the maximum inline oscillating velocity of the cylinder, \( \nu \) is the fluid viscosity; (4) the structural damping ratio \( \zeta = c / (2 \sqrt{k m}) \), where \( c \) is the structural damping and \( k \) is the stiffness of the spring. In all simulations, the cylinder is forced to periodically oscillate 20 cycles in the flow direction. The latter half computational data is used to analyze the vibration features of the cylinder in both conditions.

RESULTS

Grid Convergence Study

The grid convergence study is conducted to verify that the solution is insensitive to the grid resolution. Then the appropriate computational mesh is chosen to carry out latter simulations. Details about three meshes are shown in table 1. These three cases are in the same conditions of a forced oscillating cylinder at KC=3.

Table1. Number of meshes for three sets of grid

<table>
<thead>
<tr>
<th>Number of mesh</th>
<th>Refinement ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse mesh</td>
<td>0.0923M</td>
</tr>
<tr>
<td>Medium mesh</td>
<td>0.185M 1.4</td>
</tr>
<tr>
<td>Fine mesh</td>
<td>0.374M 1.4</td>
</tr>
</tbody>
</table>

Fig.2 Drag coefficients for three sets of meshes

The time histories of drag coefficients are shown in Fig. 2. From this figure, it can be found that time series of drag coefficients calculated from three meshes are very similar and errors only occur at reverse points. The cause of the error may result from the complexity of the flow field when the cylinder reverses. The meshes around the cylinder of the chosen one is shown in Fig. 3.

Fig.3 Computational mesh around the cylinder

Fig.4 Vortex evolution in an oscillating period: (a) T=36.0s; (b) T=36.24s; (c) T=36.48s; (d) T=36.72s; (e) T=36.96; (f) T=37.2. Arrows refer to the direction of the cylinder motion.

From previous studies of Williamson (1985) and Sarpkaya (1986), it can be known that the flow regime of the cylinder belongs to the attached vortices regime when KC=3. A pair of symmetric vortices generates and falls out of the cylinder in each half oscillating period. While no vortex shedding phenomenon happens in an oscillating period. The pair of vortices falls out of the cylinder when the cylinder reaches its rightmost or leftmost position and begins to reverse. The flow regime of the cylinder is shown in Fig. 4. A symmetric vortex street is generated after multi-oscillating periods and a pair of symmetric vortices falls out the cylinder in each half oscillating period.
Free Decay Test

In this part, the cylinder is freely vibrating and the free decay test is taken to confirm the stiffness of the spring. The time history of the cross-flow displacement of the cylinder is shown in Fig. 5. And the FFT transform of is shown in Fig. 6. The vibration frequency of the free decay shown in Fig. 6 is 0.65Hz. Then the vibration frequency of the cylinder in water is set to be 1.53s in this paper.

![Free decay of a circular cylinder in still water with an initial cross-flow velocity of 0.4m/s](image)

Fig. 5 Free decay of a circular cylinder in still water with an initial cross-flow velocity of 0.4m/s

![FFT transform of the cross-flow time history displacement of the cylinder](image)

Fig. 6 FFT transform of the cross-flow time history displacement of the cylinder

Forced Oscillating Cylinder

For forced oscillating cylinder cases, the cylinder is forced to oscillate in the x direction and is not allowed to vibrate in the y direction.

\[ KC=6 \]

The maximum Reynolds number is 1000 in this case. According to previous experiments of Williamson (1985) and Sarpkaya (1986, 1995), we can know that when KC=6 the flow regime of the cylinder still belongs to the attached vortices regime as KC=3. While a pair of asymmetric vortices genetates in each half oscillating period, which leads to the asymmetric falling out of vortices pair. And the “M” type of flow regime is generated as shown in Fig. 7.

![Vorticity graph at KC=6 (T=27s)](image)

Fig. 7 Vorticity graph at KC=6 (T=27s)

![Vortex evolution in an half oscillating period at KC=6:](image)

(a) T=27.2s; (b) T=27.4s; (c) T=27.6s; (d) T=27.8s; (e) T=28.0s; (f) T=28.2s. Arrows refer to the direction of the cylinder motion.

From Fig. 8(a) to 8(f), the vortices generates and falls out process can be summarized as: (I) A vortex “A” in anti-clockwise direction is generated in the bottom surface of the cylinder when the cylinder reaches its leftmost position and begins to reverse; (II) The vortex “B”, generated in the previous half period in clockwise direction, around the surface of the cylinder is divided into two parts (b1 and b2) and move upward and downward respectively along the surface of the cylinder; (III) Then a pair of vortices (b1 and C) in adverse direction gets into a group and begin to separate from the cylinder. While the vortex “b1” in the bottom side of the cylinder separates alone with the strengthening of the vortex “A”; (IV) In the end of this half cycle, vortex “b1” and vortex “b2” merge together and a stronger vortex “B*” is generated, while vortex “D” separated in the previous cycle is going to merge with vortex “A”. And a new vortex “E” is generated above vortex “A” at the bottom surface of the cylinder which is similar to the phenomenon shown in Fig. 8(a).
KC=12

The maximum Reynolds number is 1000 in this case. When KC=12, the flow regime of the cylinder locates in the transverse vortex street regime. And vortex shedding occurs during the process of each half period of the oscillatory motion. As shown in Fig. 9, a pair of vortices sheds in an oscillating period. And the trail of vortices convects away at around 90° to the oscillating direction of the cylinder, which is in agreement with experiments of Williamson (1985).

Fig. 9 Vorticity graph at KC=12

From Fig. 10(a) to 10(f), the vortices generating and vortex shedding can be summarized as followed: (I) A clockwise vortex “A” has been shed in the last half oscillating period when the cylinder reaches its rightmost position. Meanwhile, a clockwise vortex “C” generates on the top surface of the cylinder; (II) The anti-clockwise vortex “B” moves around the cylinder from the bottom surface to the top surface, while vortex “C” moves to the bottom side during the reverse process; (III) When the cylinder reaches its leftmost position, the vortex “B” is intended to shed from the cylinder and the vortex “C” gets stronger during the half oscillating process; (IV) At the preliminary stage of the reverse process, the vortex “B” sheds and groups with vortex “A”. Then the vortices pair moves away at around 90° to the flow direction; (V) In the end of this half process, the evolution of vortex “C” and vortex “D” is similar to vortex “A” and vortex “B”. Vortex “C” sheds from the cylinder in the terminal stage of the process. In the whole oscillating cycle, two vortices convect away from the cylinder respectively in each half oscillating period. And vortex shedding only happens on one side of the cylinder.

Freely Vibrating Cylinder

For the freely vibrating case, the cylinder is also forced to oscillate in the $x$ direction as the forced oscillating cylinder case. And the cylinder is allowed to vibrate in the $y$ direction resulting from the fluctuation of pressure difference between the top and bottom side of the cylinder.

KC=6

The time series of cross-flow displacement of the cylinder is shown in Fig. 11 at KC=6 in the freely vibrating condition. The vibrating period in the cross-flow direction is 0.85s which is 0.35 of the oscillating period in the flow direction. From this figure, it can be known that the cross-flow displacement is extremely small, resulting from the small lift force coefficient.

Fig. 12 shows comparison on time series of lift force coefficients between fixed cylinder and freely vibrating cylinder. The lift force coefficient amplitude of the freely vibrating cylinder is larger than that of the fixed cylinder and the phase difference exists, which results from the cross-flow vibration. Fig. 13 is the vortex evolution of the freely vibrating cylinder in a half oscillating period. The flow regime is similar to that of the fixed cylinder shown in figure 7 where a pair of vortices falls out in each half period and the “M” type of flow regime is also appears. The vortex is stronger in the freely vibrating condition which causes a larger pressure difference between both sides of the cylinder. Finally the larger lift force is generated in the cross-flow direction.
Fig. 11 Time series of displacement in cross-flow direction at KC=6

Fig. 12 Time series of lift force coefficient at KC=6

Fig. 13 Vortex evolution in a half oscillating period at KC=6 of freely vibrating cylinder: (a) T=27.2s; (b) T=27.4s; (c) T=27.6s; (d) T=27.8s; (e) T=28.0s; (f) T=28.2s. Arrows refer to the direction of the cylinder motion.

KC=12

The time series of cross-flow displacement of the cylinder is shown in figure 13 at KC=12 in the freely vibrating condition. The vibrating period in the cross-flow direction is 1.25s which is 0.52 of the oscillating period in the flow direction. From this figure, it can be seen that the cross-flow displacement is also extremely small as that of the KC=6 condition.

Fig. 14 Time series of displacement in cross-flow direction at KC=12

Fig. 15 Time series of lift force coefficients at KC=12

Fig. 16 Vortex evolution in an oscillating period at KC=12 of the freely vibrating cylinder: (a) T=75.6s; (b) T=76.56s; (c) T=77.52s; (d) T=78.48s; (e) T=79.44; (f) T=80.4s. Arrows refer to the direction of the cylinder motion.
Fig. 15 shows the comparison of time series of lift force coefficients between fixed cylinder and the freely vibrating cylinder. The lift force coefficient amplitude of the freely vibrating cylinder is larger than that of the fixed cylinder as KC=6. Fig. 16 is the vortex evolution of the freely vibrating cylinder in a half period. From the figure, it can be concluded that the flow regime still belongs to the traverse street regime. And the vortex shedding direction is perpendicular to the flow direction. However, vortex shedding only happens on the bottom side of the cylinder, which is opposite to that of the fixed cylinder condition. The result is in good agreement Kozakiewicz et al., (1996).

CONCLUSION

In this paper, numerical simulations of a fixed cylinder and a freely vibrating cylinder experiencing relative oscillatory flow are carried out by naoe-FOAM-SJTU solver. Flow regimes, vortex evolution process and force coefficients are analyzed. Phenomena of numerical simulations are in good agreement with previous experiment and simulations of Williamson (1985) and Kozakiewicz et al., (1996).

Results comparison show that the lift force coefficient is in opposite phase with the time series of cross-flow displacement. Phase difference exists between lift force coefficients and cross-flow displacement in KC=6. With the increase of KC number, the difference of lift force coefficient between the fixed cylinder and the freely vibrating cylinder is more obvious that can be seen from Fig.15. From the vortex evolution process, it can be known that the vortex shedding direction changes to the other side of the cylinder due to the cross-flow vibration when KC=12.

ACKNOWLEDGEMENTS

This work is supported by the National Natural Science Foundation of China (51490675, 11432009, 51579145), Chang Jiang Scholars Program (T2014099), Shanghai Excellent Academic Leaders Program (17XD140230), Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning (2013022), Innovative Special Project of Numerical Tank of Ministry of Industry and Information Technology of China(2016-23/09) and Lloyd's Register Foundation for doctoral student, to which the authors are most grateful.

REFERENCES


